

# Status and perspectives of hyperon production and electromagnetic decays with HADES at FAIR

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**Abstract.** The Hades spectrometer is a versatile detector device operating at the SIS18 synchrotron at GSI Darmstadt with a vital list of results on strangeness production including  $\Lambda(1405)$  and  $\Sigma(1385)$  exclusive production cross-sections,  $\Lambda$  polarization,  $\Lambda$ -p correlation and Kaons in-medium. With the upgrade of the SIS18 synchrotron for the FAIR facility and the upgrade of HADES with a new Forward Detector, the experiment will have a unique opportunity to study also excited hyperon states. Among others, production and electromagnetic decays of excited  $\Lambda$  and  $\Sigma$  hyperons states,  $\Xi^-$  cascade spectroscopy and  $\Lambda$ - $\Lambda$  production and correlation are planned. We have studied the reconstruction feasibility using two benchmark channels of  $\Lambda(1520) \rightarrow \Lambda e^+ e^-$  Dalitz decay and exclusive  $\Xi^-$  production in  $pp \rightarrow \Xi^- K^+ K^+ p$  reaction. The Forward Detector consisting of a forward tracker made of PANDA straw tubes prototypes and a RPC time of flight detector will enlarge HADES acceptance to forward angles ( $0.5-7^\circ$ ), important for  $\Lambda$  tagging. The magnetic field-free forward region will require employment of kinematical refit and neural networks analysis methods to perform particle identification. In this contribution highlights of strangeness production in p-p and p-A reactions will be presented together with perspectives for the future hyperon programme.

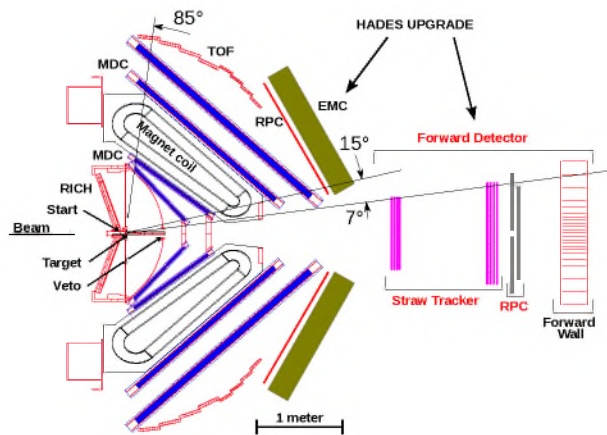
## 1. Introduction

HADES (High Acceptance DiElectron Spectrometer) [1] is a magnetic spectrometer detector operating since 2002 at the SIS18 synchrotron in GSI Helmholtz Institute for Heavy Ion Research in Darmstadt (Germany). It is a universal experimental apparatus allowing to measure various charged hadrons (protons, pions, Kaons) and leptons (electrons and positrons), resulting from particle production with pion, proton and heavy ion-induced reactions on proton and various nuclear targets in the beam energy range between 1 GeV and 3.5 GeV. It features an excellent mass resolution of  $\Delta M/M \approx 2.5\%$  in the  $\rho/\omega/\phi$  vector mesons mass region. With its versatility, it is an excellent tool to study hadrons' properties in vacuum or cold and dense baryonic matter [2] complementary to the region of large temperatures and smaller or even negligible net baryon densities as probed by experiments at SPS (CERN), RHIC (USA) and LHC. Results obtained in the last ten years by HADES showed that baryonic resonances, seen as excitation of bare nucleons, play a fundamental role in the processes that define the physics at finite baryonic densities and are important sources of meson production at these energies, that one can speak about a “resonance matter” emerging from heavy ion collisions at kinetic energies of few GeV. Using nucleon-nucleon and pion-nucleon reactions, HADES studies also the resonance structure



in vacuum and investigates their production and decay mechanisms. In particular the study of the so-called Dalitz decay of the resonances into the  $Ne^+e^-$  final state provides valuable information about their internal structure [3].

Starting from 2025, HADES will operate within the new experimental facility of FAIR, allowing to measure various reactions with beam energies up to 10 GeV, a region where the resonance dominated production of the matter changes into string fragmentation. To prepare for these new experimental challenges, the HADES spectrometer is currently undergoing several hardware upgrades: a new and faster readout electronics (DAQ), an upgrade of the RICH detector to improve on the dilepton identification, implementation of an Electromagnetic Calorimeter (ECAL) for gamma reconstruction and a Forward Detector (FD) to add particle tracking capabilities in the forward direction. A total gain of factor 50 in the counting rate capabilities is expected from these upgrades. The new setup opens up the possibility to detect the radiative decay of hyperons and hyperon resonances. The upgraded set-up will be utilized in the FAIR Phase-0 programme starting already this year making use of the upgraded SIS18 machine. A schematic drawing of the upgraded setup is shown in the Fig. 1.



**Figure 1.** Cross-section of the HADES detector with the installed Forward Detector upgrade.

Measurements of the electromagnetic decays of excited hyperons via virtual and real photons provide an important insight into their structure. The theoretical work [4] has been published in middle 1980s but there was little experimental progress in last thirty years. Hyperon structure can be probed by measurements of the electromagnetic form-factors which are in general a function of the squared four momentum transfer ( $q^2$ ) of the virtual photon exchanged either in electro-production experiments (space-like domain where  $q^2 < 0$ ), or in Dalitz decays (into  $\Lambda(\Sigma^0)e^+e^-$ ) or  $e^+e^-$  annihilation experiments (the latter two probe time-like domain where  $q^2 > 0$ ). There are only few measurements of the Hyperon  $\rightarrow \gamma\Lambda(\Sigma^0)$  decays available [5, 6]. Recently the CLEO collaboration provided the first measurement of hyperon production in an annihilation experiment at large momentum transfers ( $q^2 = 14.2 \text{ GeV}/c^2$ ) which indicate the important role of correlation effects between quarks [7]. Indeed quark models predict a strong dependence of the branching ratios on the hyperon structure, and in particular effects of quark correlation [4]. Models including meson clouds effects predict large effects reflected in hyperon electromagnetic transition form-factors [8]. Results from HADES on both photon and dielectron decays like  $\Lambda(1520) \rightarrow \Lambda\gamma(e^+e^-)$  and  $\Lambda(1405) \rightarrow \Sigma^0(\Lambda)\gamma(e^+e^-)$  will have therefore significant impact on understanding the electromagnetic structure of the strange resonances in the region of small  $q^2$  (scale of a few MeV) where effects of the vector meson ( $\rho/\omega/\phi$ ) contribution are predicted to be large [9]. The collected data will allow also for a study of differential distributions of hyperons in non-Dalitz two step weak decays like  $\Sigma^0 \rightarrow \Lambda\gamma \rightarrow p\pi^-\gamma$ . Any deviations from the expected flat distribution of the angle between outgoing proton and photon in the  $\Lambda$  reference frames will be a signature of baryonic P and CP violations, an important topic in baryogenesis,

**Table 1.** List of signal (S) and background (B) channels for simulated benchmark reactions.

$\Xi^-$ production			$\Lambda(1520) \rightarrow \Lambda e^+ e^-$ production		
Channel	$\sigma$ ( $\mu\text{b}$ )	Type	Channel	$\sigma$ ( $\mu\text{b}$ )	Type
$pK^+K^+\Xi^-$	4.8	S	$pK^+\Lambda(1520) \rightarrow pK^+\Lambda e^+e^-$	$130 \times 7.8 \times 10^{-5}$	S
$pp\pi^+\pi^+\pi^-\pi^-$	600	B	$pK^+\Lambda(1520) \rightarrow pK^+ + X$	130	B
$p\Lambda K_S^0\pi^+$	100	B	$pp\pi^+\pi^-\pi^0$	100	B
$p\Lambda K^+\pi^+\pi^-$	30	B	$pp\pi^+\pi^-\pi^0\pi^0$	20	B
$n\Lambda K_S^0\pi^+\pi^+$	30	B	$pn\pi^+\pi^+\pi^-\pi^0$	7	B
$p\Sigma^0 K_S^0\pi^+$	20	B	$p\Lambda K^+\pi^0$	43	B
$ppK_S^0K_S^0$	20	B	$p\Lambda K^+\pi^0\pi^0$	10	B
			$p\Lambda K^+\pi^0\pi^0\pi^0$	7	B
			$n\Lambda K^+\pi^+\pi^0$	20	B
			$p\Sigma^0 K_S^0\pi^+$	18	B

where CP violation is a key feature to explain the observable asymmetry between matter and anti-matter [10].

The HADES collaboration measured an enhanced  $\Xi$  cascade production in ArKCl [11] and pNb [12] reactions. It was shown that the measured cascade yield is significantly higher by a factor 10 to 100 than in the considered different theoretical models. A similar enhancement observed in the p+Nb system points to effects appearing already in cold nuclear matter. Production on correlated nucleon pairs or excitation of higher mass resonances with a significant decay branch to  $\Xi KK$  have been considered as a possible explanation of the excess. But until now, no reference measurement in the NN system has been performed. Deuteron beam on a hydrogen target, or proton on a light nucleus are most suitable reactions for performing these studies.

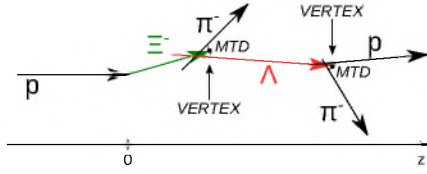
Two types of benchmark channels for proton-proton collisions at 4.5 GeV kinetic beam energy have been chosen to study the feasibility of measurements of the interesting reactions with the new HADES detector, namely production of Dalitz pairs from excited hyperons  $\Lambda(1520)$ ,  $\Sigma(1385)$  and  $\Lambda(1405)$  and production of  $\Xi^-$ .

## 2. Simulation and signal reconstruction

Both benchmark channels have been simulated using the Pluto Monte-Carlo package [13]. Signal and background channels for both reactions are listed in Table 1 and have been selected to accurately represent the possible background including direct (phase-space) proton and multi-pion production as well as channels with associated strangeness production and dilepton sources like  $\pi^0$ . The effective signal for  $\Lambda(1520)$  Dalitz decay includes the branching ratio of  $7.8 \times 10^{-5}$ . The other possible decay channels for  $\Lambda(1520)$  are considered here as background channels. In a similar manner  $\Lambda(1405)$  and  $\Sigma(1385)$  Dalitz decay channels have been considered with branching ratios of  $6.2 \times 10^{-5}$  and  $9.1 \times 10^{-5}$  respectively.

The signal has been simulated using the GEANT3 package including HADES geometry description and realistic detector responses in the digitization step.

For both benchmark channels the interesting final state particles are protons and pions originating from  $\Lambda$  weak decay ( $\Lambda(1520)$ ,  $\Xi^-$ ) and di-leptons ( $\Lambda(1520)$ ). Since HADES is insensitive to neutral particles,  $\Lambda$  has been reconstructed using only charged decay channel  $p + \pi^-$  (BR = 69%). The simulated phase-space for the  $\Xi^-$  signal channel shows that most pions will be registered in HADES (angles above  $10^\circ$ ) while protons (79% for  $\Xi^-$  and 49%

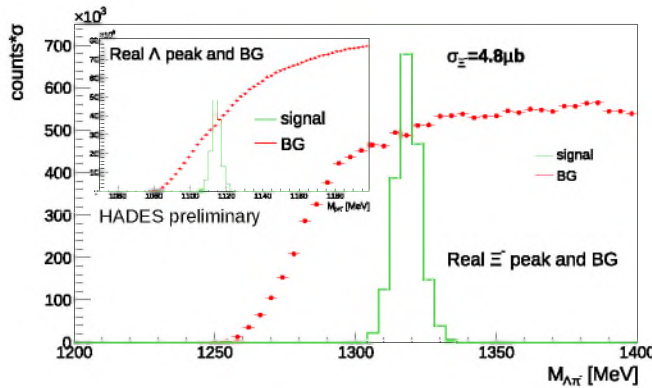


**Figure 2.**  $\Xi^-$  decay topology and applied cuts. Dashed lines represent maximal tracks distance (MTD) cut and the dot symbolizes reconstructed decay vertex.

for  $\Lambda(1520)$  only in the Forward Detector (angles below  $8^\circ$ ). Therefore the following particle identification strategy has been used: (i) each particle flying into the FD is treated as proton, (ii) hyperons are reconstructed using protons from the FD and pions from HADES, (iii) pions in HADES are identified using TOF and momentum measurement, (iv) dileptons are identified using the standard HADES method of ring finding in the RICH detector.

$\Xi^-$  decay was reconstructed using the decay chain where the  $\Xi^-$  particle decays weakly into a  $\Lambda$  and  $\pi^-$  pair, and  $\Lambda$  further decays into  $p\pi^-$  pair (Fig. 2). In order to effectively reduce combinatorial and misidentification background from the signal and background channels, the following set of topological cuts has been applied: (i) maximal distance between (MTD)  $\Lambda$  decay particles  $< 25$  mm, (ii) position of the  $\Lambda$  decay vertex z-coordinate  $-20 \text{ mm} < z_\Lambda < 30 \text{ mm}$ , (iii) maximal distance between (MTD)  $\Xi^-$  decay particles  $< 20$  mm, (iv) position of the  $\Xi^-$  decay vertex z-coordinate  $-50 \text{ mm} < z_{\Xi^-} < 30 \text{ mm}$ .

The cuts have been optimized for the best significance  $\varepsilon = S^2/(S + B)$ , where  $S$  is total signal and  $B$  is integrated background within  $3\sigma$  range of signal peak. The resulting  $\Xi^-$  and  $\Lambda$  peaks are shown in Fig. 3. The estimated reconstruction efficiency is 0.7 %.

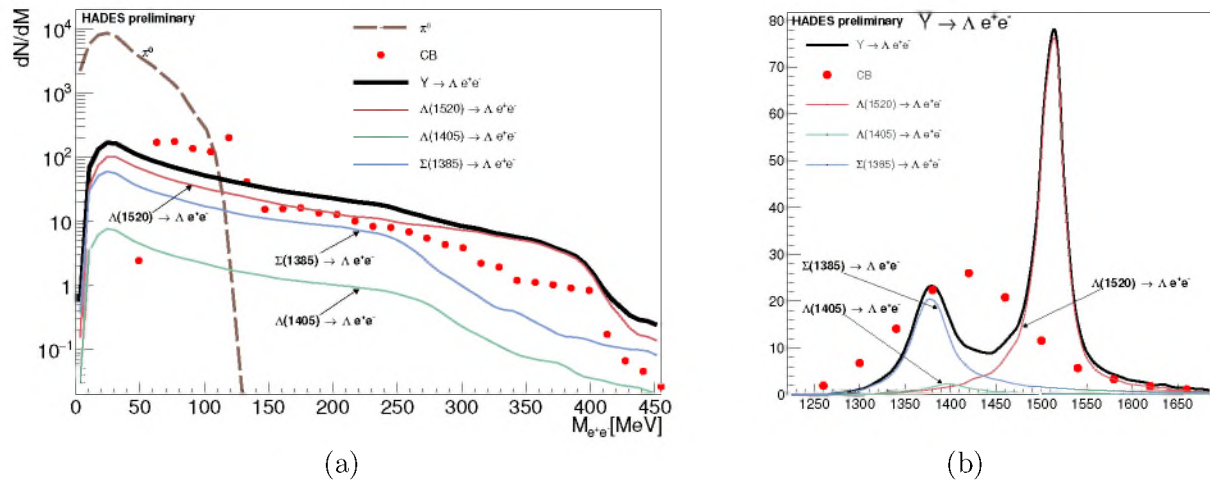


**Figure 3.** Reconstruction of signal and background for  $\Xi^-$  production. The inset figure shows the reconstructed signal and background for intermediate  $\Lambda$ . Figure coloured online.

The electromagnetic decays of hyperons were considered in the reaction where the initial hyperon decays into a pair of  $\Lambda$  and a virtual photon  $\gamma^*$  decaying into dilepton pair  $e^+e^-$ , and has been reconstructed in a similar manner to  $\Xi^-$ . The difference is that the hyperon decay process occurs at the point of production since  $\Lambda(1520)$  is a short living resonance. The  $\Lambda$  decay occurs at a displaced vertex and the  $e^+e^-$  pair also originates from the  $\Lambda(1520)$  production vertex. Only of cut of MTD  $< 20$  mm has been applied for  $\Lambda$  decay. The opening angle for the dilepton pair is  $> 4^\circ$  to reduce conversion background.

Figure 4 (a) shows the reconstructed dilepton spectrum. The brown dash line represents dileptons from  $\pi^0$  decays. Red dots show combinatorial background from leptons originating from different pairs. The black solid line shows the total dilepton spectrum originating from virtual photon decays from  $\Lambda(1520)$ ,  $\Lambda(1405)$  and  $\Sigma(1385)^+$  resonances (red, green and blue lines respectively). Figure 4 (b) shows peaks for  $\Lambda(1520)$ ,  $\Sigma(1385)^+$  and  $\Lambda(1405)$  with a cut on dilepton mass above the  $\pi^0$  mass ( $m_{e^+e^-} > 150 \text{ MeV}$ ). The black solid line is total signal. The estimated reconstruction efficiency is 0.5 %.

The count rates for the aforementioned reactions have been considered in light of the following assumptions: (i) expected trigger rate 200 kHz resulting from the planned upgrade of



**Figure 4.** Dilepton spectrum from signal  $\gamma^*$  and background  $\pi^0$  sources (a) and reconstructed  $\Lambda(1520)$ ,  $\Sigma(1385)^+$  and  $\Lambda(1405)$  peaks (b). See text for details. Figure coloured online.

the HADES DAQ, (ii) trigger dead time at 50 %, (iii) beam rate  $10 \times 10^8$  part/s, (iv) beam duty cycle 50 %, (v) polyethylene (PE) target density  $1.4 \times 10^{24}$  atoms/cm<sup>2</sup> (luminosity of  $1.4 \times 10^{32}$  cm<sup>-2</sup> s<sup>-1</sup>), (vi) reconstruction efficiencies of 0.7 % and 0.5 % for  $\Xi^-$  production and  $\Lambda(1520) \rightarrow \gamma e^+e^-$  respectively. Finally, a  $1.18 \Xi^-$ /s production rate and a total of  $2.8 \times 10^6 \Xi^-$ s are expected within four weeks of beam time, and  $1.75 \times 10^{-3}$  events/s with a total of  $4.3 \times 10^3 \Lambda(1520) \rightarrow \gamma e^+e^-$  events within the same period.

### 3. Summary

The feasibility studies showed that measurement of both benchmark channels is possible with HADES and only with use of the Forward Detector. In case of both benchmark channels the desired four weeks of beam taking will be sufficient to obtain enough statistics. However low count rates originating from very low branching ratios for Dalitz decays of hyperons suggest that it would be better choice to use a solid polyethylen target in the experiment.

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### References

- [1] Agakishiev G *et al.* (HADES) 2009 *EPJ* **A41** 243–277 (*Preprint* 0902.3478)
- [2] Lorenz M (Hades) 2018 *PoS CPOD2017* 016
- [3] Adamczewski-Musch J *et al.* (HADES Collaboration) 2017 *Phys. Rev. C* **95**(6) 065205
- [4] Kaxiras E, Moniz E J and Soyeur M 1985 *PR* **D32**(3) 695–700
- [5] Olive K A *et al.* (Particle Data Group) 2014 *Chin. Phys.* **C38** 090001
- [6] Taylor S *et al.* (CLAS Collaboration) 2005 *Phys. Rev. C* **71**(5) 054609
- [7] Dobbs S, Tomaradze A, Xiao T and Seth K K 2016 *AIP Conference Proceedings* **1735** 080003
- [8] Ramalho G, Peña M T, Weil J, van Hees H and Mosel U 2016 *Phys. Rev. D* **93**(3) 033004
- [9] Williams R A, Ji C R and Cotanch S R 1993 *PR* **C48**(3) 1318–1322
- [10] Nair S S, Perotti E and Leupold S 2018 (*Preprint* 1802.02801)
- [11] Agakishiev G *et al.* (HADES Collaboration) 2009 *PRL* **103**(13) 132301
- [12] Agakishiev G *et al.* (HADES collaboration) 2015 *PRL* **114**(21) 212301
- [13] Frohlich I *et al.* 2007 *PoS ACAT2007* 076 (*Preprint* 0708.2382)